

DARK ATOMS OF DARK MATTER AND THEIR STABLE CHARGED CONSTITUENTS

Maxim Yu. Khlopov^{1,2,3}

¹ *National Research Nuclear University "Moscow Engineering Physics Institute",
115409 Moscow, Russia*

² *Centre for Cosmoparticle Physics "Cosmion" 115409 Moscow, Russia*

³ *APC laboratory 10, rue Alice Domon et Léonie Duquet
75205 Paris Cedex 13, France*

E-mail: khlopov@apc.univ-paris7.fr

Direct searches for dark matter lead to serious problems for simple models with stable neutral Weakly Interacting Massive Particles (WIMPs) as candidates for dark matter. A possibility is discussed that new stable quarks and charged leptons exist and are hidden from detection, being bound in neutral dark atoms of composite dark matter. Stable -2 charged particles O^{--} are bound with primordial helium in O-helium (OHe) atoms, being specific nuclear interacting form of composite dark matter. The positive results of DAMA experiments can be explained as annual modulation of radiative capture of O-helium by nuclei. In the framework of this approach test of DAMA results in detectors with other chemical content becomes a nontrivial task, while the experimental search of stable charged particles at LHC or in cosmic rays acquires a meaning of direct test for composite dark matter scenario.

1. Introduction

It was shown recently^{1,2} that new stable charged particles can exist, if they are hidden in neutral atom-like states. To avoid anomalous isotopes overproduction, stable particles with charge ± 1 (like tera-electrons^{3,4}) should be absent, so that stable negatively charged particles should have charge -2 only. This possibility cannot take place in SUSY models but a row of alternative models predict such particles (see Refs. in²).

In the asymmetric case, corresponding to excess of -2 charge species, O^{--} , they bind in "dark atoms" with primordial ${}^4\text{He}$ as soon as it is formed in the Standard Big Bang Nucleosynthesis. Such dark atoms, called O-helium (OHe), are assumed to be the dominant form of the modern dark matter, giving rise to a Warmer than Cold dark matter scenario.^{2,5}

Interaction of OHe with nuclei in underground detectors can explain positive results of dark matter searches in DAMA/NaI (see for review⁶) and DAMA/LIBRA⁷ experiments by annual modulations of radiative capture of O-helium, resolving the controversy between these results and the results of other experimental groups.

2. Some features of O-helium Universe

As soon as primordial helium is formed in the Big bang nucleosynthesis, all free O^{--} are trapped by ${}^4\text{He}$ in O-helium "atoms" (${}^4\text{He}^{++}O^{--}$). The radius of Bohr orbit in these "atoms"^{1,2} $R_o \sim 1/(Z_O Z_{He} \alpha m_{He}) \approx 2 \cdot 10^{-13}$ cm is nearly equal to the radius of helium nucleus.

Due to nuclear interactions of its helium constituent with nuclei in the cosmic plasma, the O-helium gas is in thermal equilibrium with plasma and radiation on the Radiation Dominance (RD) stage, while the energy and momentum transfer from plasma is effective. The radiation pressure acting on the plasma is then transferred to density fluctuations of the O-helium gas and transforms them in acoustic waves at scales up to the size of the horizon.

At temperature $T < T_{od} \approx 200S_3^{2/3}$ eV the energy and momentum transfer from baryons to O-helium is not effective^{1,2} and O-helium gas decouples from plasma. It starts to dominate in the Universe after $t \sim 10^{12}$ s at $T \leq T_{RM} \approx 1$ eV and O-helium “atoms” play the main dynamical role in the development of gravitational instability, triggering the large scale structure formation. The composite nature of O-helium determines the specifics of the corresponding warmer than cold dark matter scenario.

Being decoupled from baryonic matter, the *OHe* gas does not follow the formation of baryonic astrophysical objects (stars, planets, molecular clouds...) and forms dark matter halos of galaxies. It can be easily seen that O-helium gas is collisionless for its number density, saturating galactic dark matter. Taking the average density of baryonic matter one can also find that the Galaxy as a whole is transparent for O-helium in spite of its nuclear interaction. Only individual baryonic objects like stars and planets are opaque for it.

3. Radiative capture of OHe in the underground detectors

3.1. O-helium in the terrestrial matter

The evident consequence of the O-helium dark matter is its inevitable presence in the terrestrial matter, which appears opaque to O-helium and stores all its in-falling flux.

After they fall down terrestrial surface, the in-falling *OHe* particles are effectively slowed down due to elastic collisions with matter. Then they drift, sinking down towards the center of the Earth. Near the Earth’s surface, the O-helium abundance is determined by the equilibrium between the in-falling and down-drifting fluxes.

At a depth L below the Earth’s surface, the drift timescale is $t_{dr} \sim L/V$, where $V \sim 400S_3$ cm/s is the drift velocity and $m_o = S_3$ TeV is the mass of O-helium. It means that the change of the incoming flux, caused by the motion of the Earth along its orbit, should lead at the depth $L \sim 10^5$ cm to the corresponding change in the equilibrium underground concentration of *OHe* on the timescale $t_{dr} \approx 2.5 \cdot 10^2 S_3^{-1}$ s.

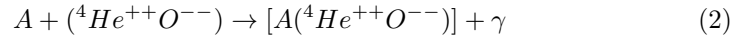
The equilibrium concentration, which is established in the matter of underground detectors at this timescale, is given by

$$n_{oE} = n_{oE}^{(1)} + n_{oE}^{(2)} \cdot \sin(\omega(t - t_0)) \quad (1)$$

with $\omega = 2\pi/T$, $T = 1yr$ and t_0 the phase. So, there is a constant concentration and its annual modulation with amplitude $n_{oE}^{(2)}$.

3.2. Potential of O-helium interaction with nuclei

The explanation² of the results of DAMA/NaI⁶ and DAMA/LIBRA⁷ experiments is based on the idea that OHe, slowed down in the matter of detector, can form a few keV bound state with nucleus, in which OHe is situated **beyond** the nucleus. Therefore the positive result of these experiments is explained by annual modulation in reaction of radiative capture of OHe



by nuclei in DAMA detector.

The approach of² assumes the following picture: OHe is a neutral atom in the ground state, perturbed by Coulomb and nuclear forces of the approaching nucleus. The sign of OHe polarizability changes with the distance: at larger distances Stark-like effect takes place - nuclear Coulomb force polarizes OHe so that nucleus is attracted by the induced dipole moment of OHe, while as soon as the perturbation by nuclear force starts to dominate the nucleus polarizes OHe in the opposite way so that He is situated more close to the nucleus, resulting in the repulsive effect of the helium shell of OHe. When helium is completely merged with the nucleus the interaction is reduced to the oscillatory potential of O^{--} with homogeneously charged merged nucleus with the charge $Z + 2$.

To simplify the solution of Schrodinger equation the potential was approximated in² by a rectangular potential, presented on Fig. 1.

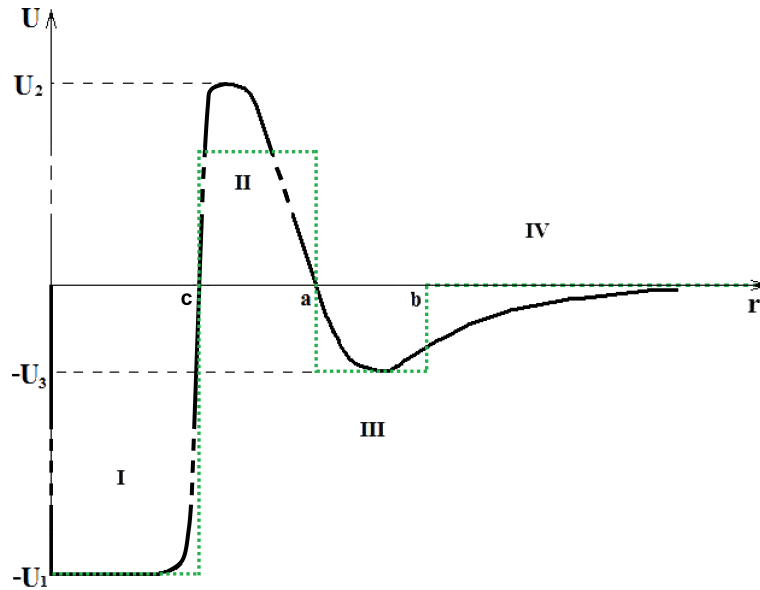


Figure 1. The approximation of rectangular well for potential of OHe-nucleus system.

Solution of Schrodinger equation determines the condition, under which a low-

energy OHe-nucleus bound state appears in the region III.

3.3. Radiative capture of O-helium by sodium

The rate of radiative capture of OHe by nuclei can be calculated² with the use of the analogy with the radiative capture of neutron by proton with the account for: i) absence of M1 transition that follows from conservation of orbital momentum and ii) suppression of E1 transition in the case of OHe. Since OHe is isoscalar, isovector E1 transition can take place in OHe-nucleus system only due to effect of isospin nonconservation, which can be measured by the factor $f = (m_n - m_p)/m_N \approx 1.4 \cdot 10^{-3}$, corresponding to the difference of mass of neutron, m_n , and proton, m_p , relative to the mass of nucleon, m_N . In the result the rate of OHe radiative capture by nucleus with atomic number A and charge Z to the energy level E in the medium with temperature T is given by

$$\sigma v = \frac{f\pi\alpha}{m_p^2} \frac{3}{\sqrt{2}} \left(\frac{Z}{A}\right)^2 \frac{T}{\sqrt{Am_p E}}. \quad (3)$$

Formation of OHe-nucleus bound system leads to energy release of its binding energy, detected as ionization signal. In the context of our approach the existence of annual modulations of this signal in the range 2-6 keV and absence of such effect at energies above 6 keV means that binding energy of Na-OHe system in DAMA experiment should not exceed 6 keV, being in the range 2-4 keV. The amplitude of annual modulation of ionization signal can reproduce the result of DAMA/NaI and DAMA/LIBRA these experiments for $E_{Na} = 3$ keV. The account for energy resolution in DAMA experiments⁸ can explain the observed energy distribution of the signal from monochromatic photon (with $E_{Na} = 3$ keV) emitted in OHe radiative capture.

At the corresponding nuclear parameters there is no binding of OHe with iodine and thallium.²

It should be noted that the results of DAMA experiment exhibit also absence of annual modulations at the energy of MeV-tens MeV. Energy release in this range should take place, if OHe-nucleus system comes to the deep level inside the nucleus. This transition implies tunneling through dipole Coulomb barrier and is suppressed below the experimental limits.

For the chosen range of nuclear parameters, reproducing the results of DAMA/NaI and DAMA/LIBRA, our results² indicate that there are no levels in the OHe-nucleus systems for heavy nuclei. In particular, there are no such levels in Xe, what seem to prevent direct comparison with DAMA results in XENON100 experiments. The existence of such level in Ge and the comparison with the results of CDMS and CoGeNT experiments need special study.

4. Conclusions

The results of dark matter search in experiments DAMA/NaI and DAMA/LIBRA can be explained in the framework of our scenario without contradiction with the

results of other groups. The proposed explanation is based on the mechanism of low energy binding of OHe with nuclei. Within the uncertainty of nuclear physics parameters there exists a range at which OHe binding energy with sodium is in the interval 2-4 keV. Annual modulation in radiative capture of OHe to this bound state leads to the corresponding energy release observed as an ionization signal in DAMA detector.

With the account for high sensitivity of the numerical results to the values of nuclear parameters and for the approximations, made in the calculations, the presented results can be considered only as an illustration of the possibility to explain puzzles of dark matter search in the framework of composite dark matter scenario. An interesting feature of this explanation is a conclusion that the ionization signal expected in detectors with the content, different from NaI, should be dominantly in the energy range beyond 2-6 keV. Therefore test of results of DAMA/NaI and DAMA/LIBRA experiments by other experimental groups can become a very nontrivial task.

The presented approach sheds new light on the physical nature of dark matter. Specific properties of dark atoms and their constituents are challenging for the experimental search. The development of quantitative description of OHe interaction with matter confronted with the experimental data will provide the complete test of the composite dark matter model. It challenges search for stable double charged particles at accelerators and cosmic rays as direct experimental probe for charged constituents of dark atoms of dark matter.

Bibliography

1. M.Yu. Khlopov, *JETP Lett.* **83**, 1 (2006).
2. M. Y. Khlopov, A. G. Mayorov and E. Y. Soldatov, *J. Phys.: Conf. Ser.* **309**, 012013 (2011).
3. S. L. Glashow, arXiv:hep-ph/0504287.
4. D. Fargion and M. Khlopov, arXiv:hep-ph/0507087.
5. M. Y. Khlopov and C. Kouvaris, *Phys. Rev. D* **78**, 065040 (2008)
6. R. Bernabei *et al.*, *Rivista Nuovo Cimento* **26**, 1 (2003)
7. R. Bernabei *et al.* [DAMA Collaboration], *Eur.Phys.J* **C56**, 333 (2008) arXiv:0804.2741 [astro-ph].
8. R. Bernabei *et al.* [DAMA Collaboration], *Nucl. Instrum. Meth. A* **592** (2008) 297 [arXiv:0804.2738 [astro-ph]].